Tradespace Exploration of the Next Generation Communication Satellites

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With this paper, we describe a tradespace exploration analysis for the next generation constellation of communication satellites resulting in a recommendation for a future system. In particular, we compare our proposal with ViaSat-3 and SpaceX's Starlink constellation. In order to arrive at a recommendation for an optimal constellation design, we first identify the design space by creating a morphological matrix and applying necessary constraints (see Table 1 for the architectural decision). The morphological matrix decisions are selected based on variability in heritage versus state-of-the-art designs, and include options with different Technology Readiness Level (TRL). The resulting 3,120 feasible architectures are evaluated using both cost and performance estimates. Costs are determined from component costs, TRL, and heritage. Performance scoring is based on a modified Signal-to-Noise Ratio (SNR) calculation, which includes technical factors such as the downlink budget and latency, as well as system factors such as crosslinks, architectures, and coverage. The final design recommendation is a Radio Frequency (RF) crosslink, bent pipe, Ka/Ku-band satellite with an electronically steered antenna and projected mass of 125 kg. The system is a constellation of 312 satellites, spread across 6 orbital planes at 444 km of altitude with global coverage and an estimated system capacity of about 2 Tbps. Estimates place the cost at $8.9 billion with a NPV of $1.4 billion over a total lifetime of ten years. Latency is expected to be around 25 ms. As with many space systems, our proposed design comes with a number of risks. Outside of typical regulatory, technological, and programmatic risks, providing satellite communications, particularly data services, comes with a unique risk: the price of user terminals. In order to provide public consumer broadband, in addition to other attractive markets such as 5G, the price of user terminals must decrease to an affordable price of $100 per terminal.

I. Nomenclature

BW = Bandwidth
DoD = Depth of Discharge
DR = Data rate
F_{BOL} = Beginning of Life Power Flux Density
F_{EOL} = End of Life Power Flux Density
G_{RX} = Receiver Gain
G_{TX} = Transmitter Gain
k = Boltzmann's Constant
L_{atm} = Atmospheric Losses
LID = Lithium Ion Density
L_{path} = Path Losses
L_{RX} = Receiver Losses
L_{TX} = Transmitter Losses
$\eta_{transfer}$ = Power transfer efficiency from solar cell to load
$\eta_{solarcell}$ = Solar cell efficiency
P_{gen} = Orbit average power generated

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P_{TX} = Transmit Power
P_{RX} = Received Power
SNR = Signal to Noise Ratio
$T_{eclipse}$ = Eclipse period per orbit
T_{sys} = System Temperature

II. Introduction

Predictions by Morgan Stanley show the market for satellite communications is expected to grow exponentially from $24B in 2018 to $128B by 2028 (see Figure 1)[1]. Driving growth in this market are upgrades to 5G networks, where satellite communications can play an important role in backhauling, tower feed, mobility, and hybrid multiplay, as well as consumer broadband [2–4].

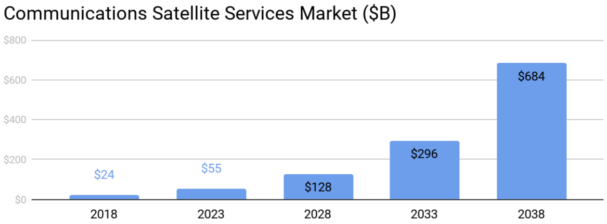


Fig. 1 Predicted growth in the satellite services market over the next 20 years.

Demand for data continues to increase for consumers, with data traffic from mobile devices increasing at over 50% per year. Consumer broadband is also expected to be an area for growth, with nearly three billion people that do not have internet access or are underserved. In the US alone, over 24 million people do not have access to terrestrial broadband and about 14 million lack LTE broadband access [4]. Only two million people globally are currently being served by satellite internet, according to the 2017 Satellite State of the Industry Report [5]. Satellite-based consumer broadband is well-suited to provide internet to these individuals, given the difficulties and marginal profit of terrestrial networks in rural areas or developing nations.

In order for the satellite industry to capture the additional demand, new, revolutionary and cost-effective constellations are necessary. Many new constellation are being proposed or developed, but which of those provide the best combination of performance and cost? And are there additional constellation architectures that dominate those designs? With this paper we aim to address those questions.

Previous works have shown processes for analyzing complex constellation systems, and methods for modeling key performance metrics and cost influences. [6] developed a model similar to the one presented in this work that incorporates both performance and cost metrics to analyze a large number of satellite constellation architectures for the SCaN program. While [6] emphasized the communication link to evaluate constellation performance, crosslink functionality was not considered, non-dominated architectures within the generated tradespace were not identified, and a method for system selection using the tool was not shown. Elbert systematically formulated the key objectives of a satellite based communication constellation from the business standpoint. The enumeration of the constellation architectures was constrained to sun synchronous orbits. The trade space was visualized in the mapping of datarate and constellation cost to identify the Pareto front and downselected designs [7]. This paper greatly expands the design space, relaxes the orbital constraint and includes key emerging technologies of tomorrows communication constellations.

We aim to approach the above questions more systematically by using a tradespace exploration technique to compare many alternative architectures with respect to performance and cost.

First, in Section III we identified the design space by creating a morphological matrix and applying constraints. After narrowing down the tradespace from 15,552 concepts to 3,120 constrained systems. Systems were evaluated for both cost and performance estimates. Costs were determined from components, TRL, and heritage. Performance scoring was based on a modified link budget equation which encapsulated crosslinks, architectures, coverage, and other relevant factors. Using normalized cost and performance metrics, the Pareto Front was identified. Then, in Section IV, we downselected into four promising systems ranging significantly in performance and costs. Section V describes financial, regulatory, marketing, and risk considerations during the implementation of those systems. Finally, Section VI concludes the paper.

III. Conceptual Design

A. Tradespace Overview

The design space of a Lower Earth Orbit (LEO) constellation was broken down into a morphological matrix, as shown in Table 1. In this table, the rows are potential decision to make when defining the system, and the columns represent one of four (or fewer) options for a corresponding decision. The decisions and their options are based on a review of other systems, and are discussed further below.

Table 1 Morphological Matrix

Decision	Option 1	Option 2	Option 3	Option 4	# Options
Crosslink Type	None	RF	Optical	-	3
Antenna Type	Parabolic or Horn	Electronically Steered	Laser	-	3
Coverage	Global (pole to pole)	Effective global (+/- 60°)	Equatorial (+/- 45°)	-	3
Relay Type	Bent Pipe	Regenerative	-	-	2
Constellation Architecture	None	Ring	Mesh	-	3
Dynamic Resource Allocation	Yes	No	-	-	2
User Terminal Type	Parabolic	Optical	Electronically Steered	-	3
Mass	< 10	10 – 100	100 – 500	500+	4
Frequency Band	X band	Ku/Ka band	V band	Optical	4
					15,552

The decisions in the morphological matrix are based on a review of existing and proposed satellite telecommunications systems [6] [8]. Given the goal of designing an advanced LEO system that competes with Viasat-3 and Starlink, many of the systems under consideration have not yet been deployed (e.g., Telesat, Starlink, Boeing). Only a handful of LEO telecommunications constellations (Iridium, Globalstar, Orbcomm) have been implemented, and none offer a data rate comparable to the FCC minimum download speed of 25 Mbps [9].

One of the first decisions we arrived at was whether the design should transmit data by crosslinking between satellites and, if so, how it should be accomplished. Many proposed designs such as Starlink feature crosslinks between satellites [], however others, such as O3b, only transmit and receive data during ground station passes []. This led to the decision regarding crosslink type, with the options of none (no crosslink), an RF crosslink, or an optical/laser-based crosslink.

In the event of a crosslink decision, a conditional decision known as constellation architecture must be selected. The first option, none, accounts for no crosslink implementation with "none". Another option is to have each satellite only link to the satellite leading and lagging within the orbital plane, known as a ring architecture. Finally, the mesh architecture captures the scenario in which satellites can communicate across planes, creating a mesh architecture.

Communication satellites can be classified into two types of data relays: "bent pipe" or "regenerative". A bent pipe relay amplifies and reroutes the received signal, while a regenerative relay demodulates, decodes, encodes, modulates, and amplifies the received data, which raises the SNR relative to the alternative [10]. This applies to constellations with and without crosslink capability.

The technology used for uplinks and downlinks is another key trade. Optical communications offer higher data rates and comparable SWaP to their RF counterparts, but are not robust to cloud-cover or weather. RF communications have less stringent pointing requirements and may be used in a range of weather conditions, though higher frequencies are susceptible to loss due to weather effects. Starlink is expected to use V-band, whereas ViaSat uses Ka-band [11] [12].

The decision regarding antenna type was driven by the current evolution of satellite antenna technology. There is the traditional option for a parabolic or horn antenna, but there is also the opportunity to use electronically steered antennas, e.g. phased arrays, which is planned for use in designs such as O3b's mPower system [13]. Finally, in the case of optical communications, the antenna is replaced by a laser. Analogous decisions must also be made for the user terminal.

There is also a decision regarding the mass of the satellite. This indicates the size of the satellite, what could be put onboard, and directly correlates to the satellite's performance (size of solar panels, antenna size, drag management needs, thermal inertia, etc.). We split this decision into four categories: less than 10 kg, 10-100 kg, 100-500 kg, and 500+ kg.

Finally, there is the decision of coverage. The goal is to compete with Viasat-3 and the proposed constellation Starlink, therefore the system needs to cover a large part of the globe - continental and regional systems would not compete in the same market. A LEO constellation cannot be limited by longitude anyway, unless the satellites are not used for large portions of their orbit. Thus, the coverage decision is based on the size of band we offer around the equator. The options are an equatorial band for ± 45° latitude, and effectively global band within ± 65° latitude, offering access to nearly all inhabited areas [14], and global, pole-to-pole, coverage.

B. Constraints

Clearly, some of these decisions interfere with one another, creating constraints. For example, if the frequency band is optical, the antenna and user terminal types must also be optical. These constraints are:

- C1: If the Frequency Band is Optical, then the Antenna Type and User Terminal Type must also be Optical (and vice versa). These three decisions must either all be Optical, or none of them are Optical.
- C2: If there are crosslinks, the type of crosslink architecture must be considered. Therefore, if the Crosslink Type is RF or Optical, the Constellation Architecture must be either Ring or Mesh. If the Crosslink Type is None, the Constellation Architecture must be None.

These constraints, and their effects, are also illustrated in the pair of decision trees in the Appendix G.

C. Metrics

With the nine system architecture design decisions determined and their inter-relating constraints identified, the next step was to determine which screening metrics to use in order to compare system designs. Communication satellites are limited by regulatory bodies, namely the FCC, on the allocation of frequency, bandwidth, and power flux density (PFD). Historically, communication satellite manufacturers struggle with profits, and many file for bankruptcy before the delivery of the system [15] [16]; for this analysis, closing the downlink budget to deliver value to stakeholders and generating a positive NPV were required; consequently, the most important metrics were determined to be cost and performance. An explanation of the quantitative analysis of the cost metric is described in Section III.E and an explanation of the performance metric approach can be found in Section III.F. Specific entries for each cost and performance metric are shown in Appendix A.

D. Algorithm

The screening metrics that were chosen highlight a trade-off in development and operation between cost and performance. In order to quantify the relationship between the two, all constrained combinations were modeled. The result of this algorithm graphically represents the entire design space, from which all the dominated solutions were identified to create the Pareto front.

E. Cost Metric Approach

The cost metric used in this analysis is a scalar from zero to ten, with zero being no cost added and ten being the most expensive option. The cost for each decision option was determined using several different methods, such as market research of commercially available components, historical FCC spectrum availability, technology heritage, and qualitative assessments of expected costs. An in-depth cost metric discussion can be found in the Appendix B.

F. Performance Metric Approach

In order to effectively assess the impact of each metric on the constellation performance, the design variables were incorporated into an equation similar to a non-normalized, multi-attribute utility function that focuses on communication performance. The algorithm begins with the downlink budget to baseline performance. It then incorporates losses from the system (e.g. path loss) and data rate to arrive at energy per bit over noise. The algorithm then includes all the decision metric factors that will either penalize or increase the performance of the link. For example, the relay loss can be thought of as a loss in SNR, since either decision affects the probability of making an error at the user terminal - thus it is a loss factor in the performance equation. The pseudo-link budget equation used to assess constellation performance is shown in Eq.(1),

$$P_{sys} = P_{tx} + G_{tx} + G_{rx} - L_p + 10\log(lat) - k - L_{relay} + gf - L_{atm} + R_{cl} \tag{1}$$

and a detailed description of the equation and its variables can be found in Appendix C.

G. Pareto Front

As can be seen in Fig. 2, the Pareto front shows a non-linear positive correlation between performance and cost. The low cost portion of the frontier experiences steep performance improvements with minimal cost increases. As the relative costs move greater than 2.5, the performance improves less compared to the increase in relative cost, indicating diminishing returns. The Pareto front offers 27 optimal non-dominated design solutions for a LEO based satellite communication constellation.

H. Reduction of Non-Dominated Solutions

A detailed analysis of the Pareto front led to a downselection of four system designs. One method used to downselect was to qualitatively analyze the Pareto front and find the points with the highest gain in performance for the lowest change in cost (e.g. the highest slope). Specific designs were also chosen to represent the full spectrum of decision options that were available along the Pareto front. Table 2 shows the details of four designs that provide the best tradeoff between cost and performance.

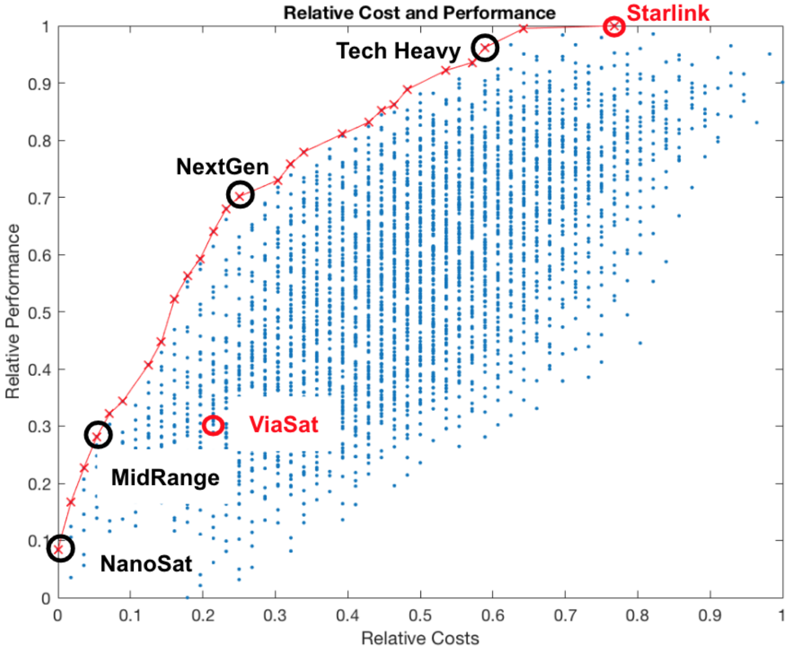


Fig. 2 Downselected Designs

NanoSat is the design with the most standardized technology (e.g. X-band frequency), but the compact form factor and lack of flight heritage results in an overall moderate TRL level. In other words, it is expected the material cost of an individual satellite will be relatively low, however developing and miniaturizing sophisticated communications payloads will result in development risks, integration problems and risks. Overall NanoSat will blur the boundaries between subsystems due to the constrained form factor.

MidRange is the transition to the next mass (and volume) category, where many of the integration and miniaturization problems should be alleviated. Additionally, the increased surface area allows for higher power generation and utilizing electronically steered antennas introduces greater capability in delivering value, such as adding beamforming functionality.

Table 2 Selected Designs

Decision/Name	NanoSat	MidRange	NextGen	Tech Heavy
Mass [kg]	10	10 – 100	100 – 500	500+
Frequency	X band	X band	Ku/Ka band	Ku/Ka band
Antenna Type	Parabolic	Electronically steered	Electronically steered	Electronically steered
Crosslink Type	None	None	RF	Optical
Relay Type	Bent Pipe	Bent Pipe	Bent Pipe	Regenerative
Architecture	None	None	Ring	Ring
Coverage	Equatorial	Equatorial	Effective Global	Effective Global
Resource Allocation	Yes	Yes	Yes	Yes
User Terminal	Electronically Steered	Electronically Steered	Electronically Steered	Electronically Steered
Cost Score [-]	0.00	0.05	0.23	0.59
Performance Score [-]	0.08	0.28	0.68	0.96

In contrast to NanoSat and MidRange, the NextGen design has effective global coverage with Ku/Ka Band frequency, and RF crosslink between satellites in a ring architecture. Similar to the transition between NanoSat and MidRange, shifting to the next mass category makes more power available per satellite. Combined with crosslink capabilities, the system can service customers in areas difficult to service, such as the maritime and aviation industries. This results in a substantially higher performance score.

Tech Heavy is similar to SpaceX's Starlink design and has low TRL level due to regenerative relays and the optical crosslinks. We expect significant developmental risk and technological challenges that may result in both cost and schedule overruns. The additional optical crosslink capability with regenerative payloads allows for a performance increase when compared to NextGen, but we also expect a significant cost increase.

IV. Detailed Design

With the design space reduced to a handful of unique systems, a detailed analysis is required to further evaluate the cost vs performance trade. We investigate specific LEO altitude for optimal operation, and the influence of coverage on system performance. The foundation of this analysis is comprised of three major technical capability estimations: a downlink budget, a power budget, and system coverage (see Fig. 3). The outputs of those functions are fed into an orbital lifetime estimator and a cost estimator, which then determine the value of the three performance metrics: \$/Megabyte, system capacity, and total cost. A summary of the detailed design functions are found in subsequent sections.

A. Link Budget

A traditional link budget is comprised of two to three parts: a downlink, an uplink, and a crosslink (if applicable). In the detailed design, the link budget is analyzed from a downlink-only perspective because the emphasis is put on delivering data to customers. The link budget starts by determining the power received at the user terminal with Eq.(2).

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - L_{atm} - L_{path} \text{ [dB]} \tag{2}$$

In this equation, P_{tx} is the power of the transmitter, G_{tx} and G_{rx} are the gains of the transmitter and receiver, respectively, L_{tx} and L_{rx} are the losses at the transmitter and receiver, L_{atm} is atmospheric losses, and L_{path} is the path loss introduced by the separation between the transmitter and receiver.

The communication system is subject to noise, with Johnson noise and amplifier noise contributing the most power to the bands of interest. Bit Error Rate (BER), the number of expected errors arising from noise in a link, is a function of the modulation scheme and $\frac{E_b}{N_0}$ (energy-per-bit). Many BER curves have been published capturing this relation for different modulation schemes, and can be used to determine the required SNR ratio for a system [17]. For a system using QPSK with 10^{-5} BER can be achieved with a SNR of 9.2 dB.

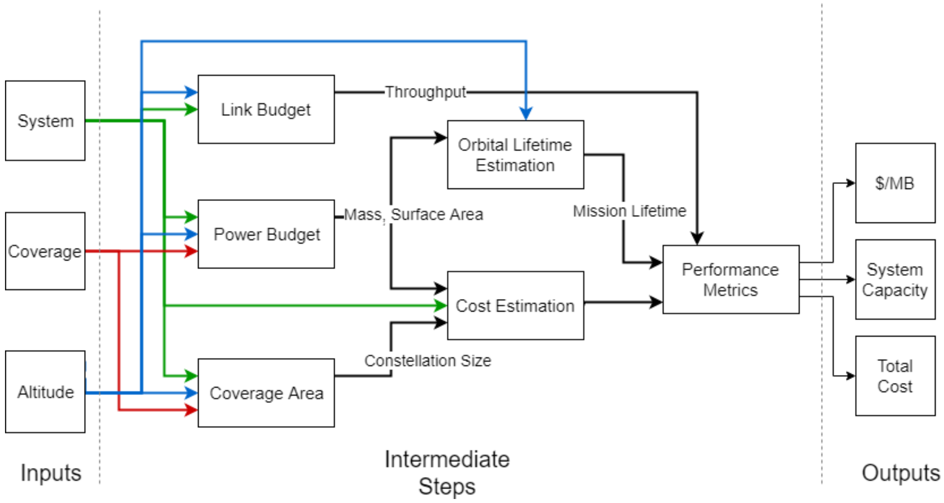


Fig. 3 Analysis Foundation

To determine the SNR of the system, denoted $\mathrm{SNR}_{\mathrm{sys}}$, Eq.(3) can be used, where P_{rx} is the power received calculated from Eq.(2) in decibels, DR is the data rate in decibels, k_{dB} is Boltzmann's constant in decibels, and T_{sys} is the system temperature in decibels. Note that SNR is equivalent to $\frac{E_b}{N_0}$ in this equation.

$$\mathrm{SNR}_{\mathrm{sys}} = P_{\mathrm{rx}} - \mathrm{DR} - k_{\mathrm{dB}} - T_{\mathrm{sys}} \text{ [dB]} \tag{3}$$

According to the Shannon-Hartley theorem, the maximum achievable data rate in a system is band-limited and noise limited, and in the case can be found as $\mathrm{DR}_{\mathrm{linear}}$ with Eq.(4), where BW is the bandwidth of the link in Hertz, P_{rx} is the power received from Eq.(2) in Watts, k is Boltzmann's constant, and T_{sys} is the system temperature in Kelvin.

$$\mathrm{DR}_{\mathrm{linear}} = \mathrm{BW}\left(1 + \frac{P_{\mathrm{rx}}}{kT_{sys}\mathrm{BW}}\right) \text{ [bps]} \tag{4}$$

By implementing a 3 dB margin, the beam-specific data rate can be found by decrementing the maximum achievable data rate in the SNR equation (Eq.(3)) until the margin criteria is met. The total system throughput then is found by multiplying the data rate per beam by the number of beams per satellite.

B. Power Budget

The power budget determines the amount of power required for full system operation in eclipse and sizes solar panels to meet the power requirement for end of life operation. According to SMAD Table 10-2, the payload consumes 40% of the spacecraft power [17], which means by estimating payload power consumed, satellite power consumed can be determined. For example, the ClydeSpace CPUT X-Band transmitter advertises less than 10 W power consumption with a single patch antenna. For NanoSat, we have assumed a gimbaled parabolic antenna configuration and an X-band radio capable of using multiple antennas simultaneously. Assuming double radio power is required to accommodate additional antennas, each antenna requires roughly 1 W for mechanical control, and ADCS can compensate for antenna movement, then roughly 26 W is required for payload operation only. This implies 65 W is required for full operation, and to add an additional margin for battery safety, the required power is rounded up to 70 W. This power estimate accounts for both bus power and payload power duty cycled over the duration of an orbit.

Using Kepler's 3rd Law, the orbital period of a single satellite can be estimated (Eq.5), and through means of geometric analysis and assuming a circular orbit (6), the percentage of the period in eclipse can be determined (7).

$$T_{orbit} = 2\pi\sqrt{\frac{(R_e + h)^3}{\mu}} \text{ [s]} \tag{5}$$

$$\alpha = 2cos^{-1}\left(\frac{R_e}{R_e + h}\right) \tag{6}$$

$$T_{eclipse} = T_{orbit} * \frac{(\pi - \alpha)}{2\pi} \text{ [s]} \tag{7}$$

Where R_e is the Earth's radius, h is the orbital altitude, and μ is the gravitational parameter for Earth.

The objective of this function is to size solar panels to meet power requirements. This is done iteratively by initializing the solar panels to an optimistic value (e.g. smaller surface area than expected), and stepping up the area incrementally until the orbit average power generated is greater than the power required.

The power generated by the solar cells is found with 8

$$P_{sa} = \frac{\frac{P_{req}T_{eclipse}}{\eta_e} + \frac{P_{req}(T_{orbit}-T_{eclipse})}{\eta_d}}{T_{orb} - T_{eclipse}} \text{ [W]} \tag{8}$$

Where a η_e and η_d are the energetic efficiencies between the solar array and load.

Solar array sizing must be done with respect to End of Life (EOL) performance. Assuming triple junction Gallium Arsenide cells, the EOL power flux density is calculated with 9 - 11

$$L_d = (1 - \epsilon_d)^{\text{satellite life}} \tag{9}$$

$$P_{BOL} = P_{sun} * \eta_{SA} * I_d cos(\theta_{inc}) \ [\frac{W}{m^2}] \tag{10}$$

$$P_{EOL} = P_{BOL} L_d \ [\frac{W}{m^2}] \tag{11}$$

Where ϵ_d is the expected yearly degradation rate due to radiation, P_{sun} is the solar constant with units $\frac{W}{m^2}$, η_{SA} is the solar cell efficiency, I_d is 0.77 for GaAs cells, and θ_{inc} is the angle of incidence of the solar ray vector onto the array. Solar array size is found using Eq.12

$$SA = \frac{P_{sa}}{P_{EOL}} \ [m^2] \tag{12}$$

Battery size is based on the system required power such that full operation is possible during eclipse periods. Healthy battery depletion practice involves setting a depth-of-discharge (DoD) threshold such that nominal operations avoid draining the battery past its DoD. This allows for longer battery lifetime and more charge cycles [17]. Eq.(13) shows a method for estimating the required battery capacity:

$$\text{Battery Capacity} = \frac{P_{gen}T_{eclipse}}{\text{DoD} * \eta_{transfer}} \text{ [kWh]} \tag{13}$$

Where P_{gen} is orbit average power generated, T_{eclipse} is from Eq.(7), DoD is the percent depth of discharge as a fraction of total battery capacity, η_{transfer} is the power transfer efficiency of the battery regulators.

To estimate the mass of the system, four assumptions were made: first, each system has propulsion; second, batteries are 32% of the satellite's mass; third, the batteries of the system are lithium-ion; and fourth, solar panels are roughly 2 kg/m^2 [18, 19]. Combining these assumptions provides us with a system for estimating the dry mass of a satellite, as shown in Eq.(14):

$$m_{dry} = \frac{\text{Battery Capacity}}{0.32 * \text{LID}} + 2 * SA \text{ [kg]} \tag{14}$$

Where *Battery Capacity* is found from Eq.(13), *LID* is the lithium-ion energy density, and *SA* is the surface area of the solar panels in m^2. To find the wet mass of the satellite it is assumed the rocket launches from Cape Canaveral and thereby satellites are released in a 28.5° inclined orbit. To achieve equatorial coverage the satellites can remain in the dropped off orbital plane while for the effective global and global coverages the orbital planes have to be changed, the required velocity change is found according to Eq.(15). V_{orbit} is the orbital velocity and Δi is the desired change in orbital inclination. The preferred propulsion system for the orbital change is ionic Electrospray Propulsion System (iEPS) with I_{sp} of $1200s$ [20]. The wet mass of the satellite is found with Eq.16, with $g = 9.81 m/s^2$.

$$\Delta V = 2V_{orbit} sin(\Delta i) \ [\frac{m}{s}] \tag{15}$$

$$m_{wet} = \frac{m_{dry}}{e^{\frac{-\Delta V}{I_{sp} g}}} \text{ [kg]} \tag{16}$$

C. Coverage Area

To estimate the required size of each downselected design, a geometric relationship was derived between satellite antenna field of view, crossover between satellites' equatorial field of view (to account for user and ground station handover) and the satellites' altitude. After analyzing constellation dynamics on a Mercator projection of Earth, it was concluded that the assumption of constellation size grows linearly as latitude coverage increases as first order approximation.

D. Orbital Lifetime Estimation

The orbital lifetime estimation is a spline extrapolation from the results produced in [21]. Based on the surface area and mass of the satellite, the orbital decay can be found for a range of altitudes. Although all orbits are placed below the Van Allen belts, radiation damage and other hardware failures are likely to become limiting factors in lifetime before orbital decay, and a maximum lifetime of ten years is assumed for each system.

E. Cost Estimation

Detailed cost estimation was implemented using the financial analysis described in Section V.A.

F. Downselected Designs

The driving performance metric for these systems is the $/MB vs. altitude function, which captures the total cost of the system, the lifetime of the system, and the total system capacity. The objective is to optimize from this metric across systems to get the best price per capacity, making it competitive from both a business and performance perspective. Different coverages produce different $/MB curves as the cost and system capacity ratio fluctuates. These curves are shown in Fig. 4. In each case, the optimum coverage value (where $/MB is minimized) was selected to represent that design for system comparisons in Section IV.G. As can be seen in Fig. 4a, the absolute minimum of $/MB occurs on the Global curve at 487 km altitude. Figure 4b shows the lowest $/MB for the MidRange constellation occurs at 505 km with Global coverage and Fig. 4c indicates that the optimal (in terms of lowest $/MB) altitude for the NextGen constellation with Global coverage occurs at 444 km. Finally, Fig. 4d shows that the Tech Heavy constellation is optimized at 411 km with Equatorial coverage. The comparison of $/MB versus altitude for the selected coverage option in each design can be found in Fig. 4e. The key characteristics of each of these systems at their optimized altitude are summarized in Table 3.

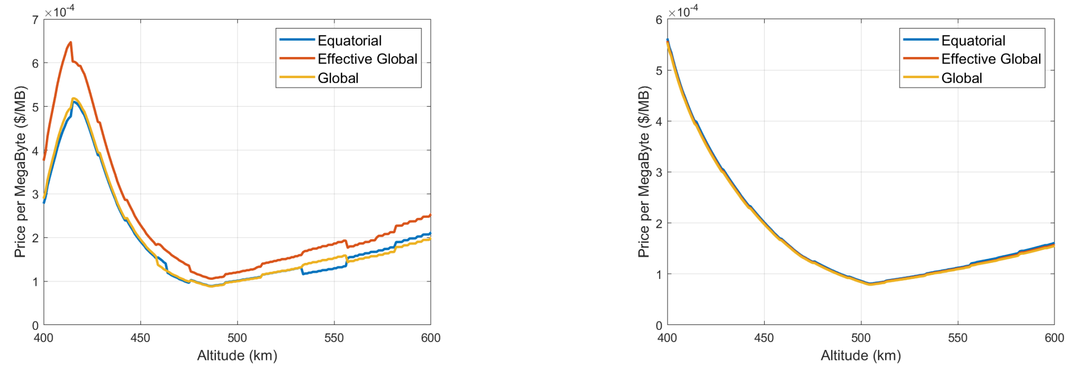
G. Detailed System Trades

Once the individual systems are vetted for optimal performance, the overall highest-performing system must be determined. Table 3 gives a side-by-side comparison of all of the systems, and Fig. 5 shows each of the system's performance metrics against one another.

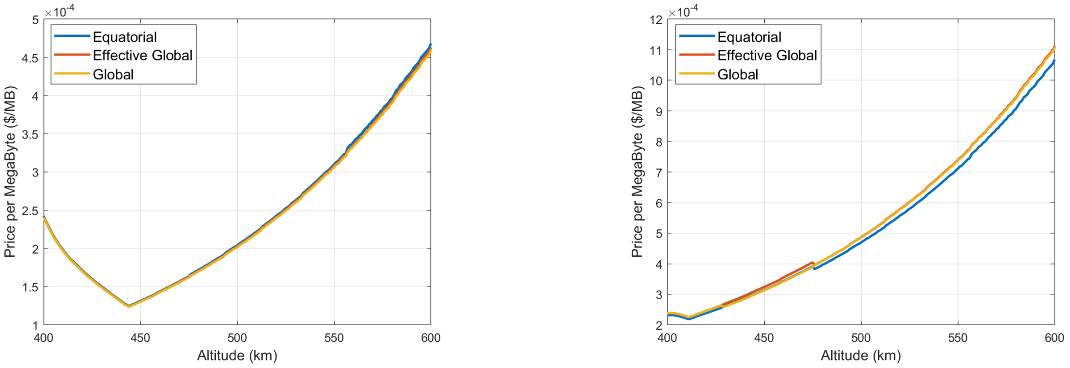
Here, the intention of this study are revisited and final downselection is aligned with mission requirements and objectives. The selection process deviates slightly from simply selecting the design with the lowest $/MB; although NanoSat has the overall smallest $/MB, it cannot compete with reference cases Starlink and Viasat in terms of capacity or throughput. Looking at altitude 444 km, NextGen exceeds ViaSat capacity and latency, has the highest NPV, and it can provide the subscribers with 10 Mbps of throughput during peak operation. Section VI gives the final system recommendation and rationale.

H. AI Implementation

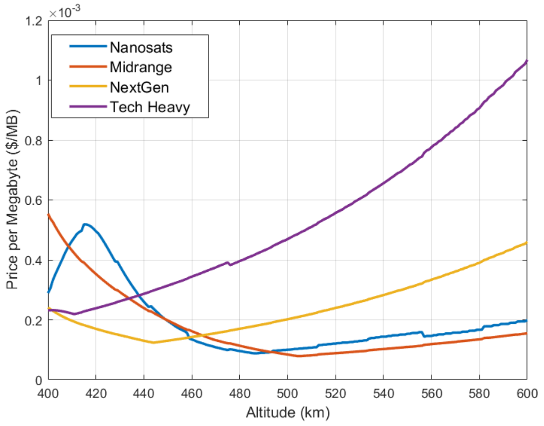
As with many fields and industries, there are a number of applications for artificial intelligence (AI) and machine learning (ML) in space and, specifically, satellite telecommunications. This could include onboard AI on the satellite itself, or ground-based systems that instruct the satellite but require more mass or power than is practical in orbit. There are a number of ways it could be included in the system, but we focused on three: health monitoring, dynamic resource allocation, and smart routing.



(a) NanoSat **(b) MidRange**



(c) NextGen **(d) Tech Heavy**

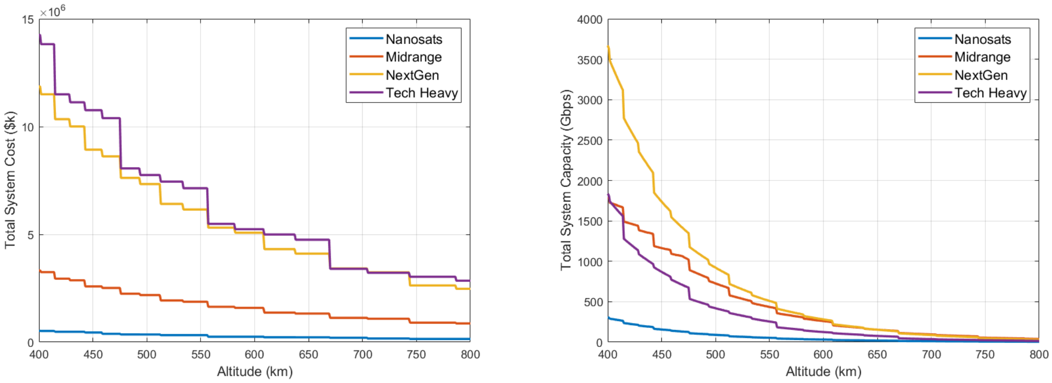


(e) Comparison of Designs for Selected Coverage

Fig. 4 Cost per Megabyte versus Altitude for the Downselected Designs

The first of these uses is health monitoring. There are massive amounts of data that can be used to understand a satellite's performance, providing information on status, health indicators, and overall behavior and environment. These data can be used to improve efficiency, diagnose problems and even predict problems before they occur. However, the amount of information is immense, and it is easy to overlook patterns or small anomalies. AI could be useful, by better interpreting the data and finding new patterns. Most of this AI will likely be ground based, given the power and complexity required to run the system, where it could provide decision support for operators. The system could also synthesize data from satellites across the constellation to more efficiently address problems.

A second use of AI is dynamic resource allocation. Efficiently distributing the satellites' power and bandwidth, as well as optimally pointing the beams, can be complex, computationally intensive questions. AI could be used to reach



(a) Total Cost Over All Systems as a Function of Altitude **(b) Total System Capacity as a Function of Altitude**

Fig. 5 Performance metrics compared for downselected designs

Table 3 Downselected Designs Comparison

Decission/Name	**NanoSat**	**MidRange**	**NextGen**	**Tech Heavy**
Mass [kg]	12.7	38.3	125	480
Frequency	X Band	X Band	Ku/Ka Band	Ku/Ka Band
Antenna Type	Parabolic	Electronically Steered	Electronically Steered	Electronically Steered
Crosslink Type	None	None	RF	Optical
Relay Type	Bent Pipe	Bent Pipe	Bent Pipe	Regenerative
Architecture	None	None	Ring	Ring
Coverage	Global	Global	Global	Equatorial
Altitude [km]	487	505	444	411
Est. Constellation Size	264	253	312	203
System Capacity [Gbps]	102.5	370.5	1832.5	3203
Development Cost	$33M	$33M	$48M	$64M
AI Software Cost	$5M	$5M	$5M	$5M
Total Satellite Cost	$38M	$1,453M	$8,112M	$12,434M
Total Launch Cost	$270M	$682M	$744M	$1,302M
Regulatory Fees	$10M	$10M	$20M	$20M
Total Constellation Cost	$356M	$2,183M	$8,929M	$13,825M
NPV	-$328M	$501M	$1,401M	-$1,748M

better solutions to this problem. Neural networks and machine learning could be used to increase efficiency. Another option would be to use genetic algorithms. The performance could be improved even further by using machine learning to determine patterns in usage and need, and allow the satellite to start acting predictively. Due to power and mass of the computing system, this AI would likely need to be ground-based.

Smart routing is a subset of resource allocation. In this case, the resource to be allocated is bandwidth across nodes in the network. At each point, a user's data could be transmitted a number of ways. The satellite could function as a bent-pipe, and simply take the user's uplink and transmit to the destination. It could take the uplink, then transmit to a ground station, send the data over cables to the destination (or to another ground station, uplink to a different satellite, and downlink to the destination). It could also take the uplink, then pass the data through many different options of crosslinks, before being beamed down to the destination, or to a ground station, etc.. At any stage, the data could go between crosslinks, to the ground and over cables, or back up to satellites. For instance, the data for a user in rural New

Mexico (headed to a company in Moscow) might go to the nearest satellite, passed by crosslink to a neighboring satellite, then beamed down to a ground station in Texas. The data might be downlinked here due to the satellites over the Eastern Seaboard being at capacity. The data could travel by cable to , before being re-uplinked and transmitted over the Atlantic by crosslinks, then beamed down to Moscow. Such a route is very complicated, but could, under specific situations, be the optimum solution. The availability of such complicated routes could improve performance of the network overall by allowing each connection in the network to operate closer to its maximum, preventing unused bandwidth in connections that are under-utilized. This would result in the entire system operating closer to peak efficiency. This is an incredibly complex computational problem, but machine learning as well as other algorithms (such as genetic algorithms) could help arrive at efficient, more optimal solutions, and thus increase throughput. The second advantage of such is a system would appear in the event of a breakdown. When a connection is blocked by weather, or if a satellite fails, an AI could identify the damaged satellite, find new paths for the information and route the data around the broken connection or satellite. This would result in an adaptive network that responds to failures, reducing downtime and increasing reliability. Due to the mass and power of the computers required for this sort of system (in addition to the needs of input from satellites across the constellation), it is recommended to be ground-based.

The only AI option incorporated in the design space was resource allocation, which was selected for each of the four downselected designs. The other two uses, health monitoring and smart routing, could be implemented for any relevant design. Hence, recommending further study to explore the exact details of how they could be implemented, the magnitude of the benefits achievable, and the possible increase in efficiency. None of these systems are necessary for the designs to work, but they have the opportunity to improve all of them. Therefore, suggesting developing these technologies and implementing them for any of the final designs.

V. Implementation Plan

A. Financial

Costs were broken down by development, satellite, launch, and regulatory costs for each of the detailed designs. Development costs were estimated based on the anticipated design time, number of full-time employees, and a salary and benefits package of \$200,000 annually. AI software cost estimation was developed in a similar way, with a annual salary of \$500,000 with ten employees for two years. The satellite costs were derived from estimated cost based on bus size, technology readiness level, and anticipated high-volume manufacturing efficiencies. Finally, the launch cost was determined by examining the satellite weight, orbital altitude, and the number of orbital planes. For “NanoSat”, the Electron Rocket from Rocket Labs was considered, whereas Falcon 9 was assumed to estimate launch costs for the other designs.

An estimate was also used for the licensing fees and includes fees associated with consultants, lawyers, International Telecommunications Union (ITU), and FCC. It was expected for Ka/Ku band to have higher fees due to their high use in the industry.

The financial costs in Table 3 represent the costs from project initiation through full constellation launch completion. To conduct an analysis of the financial viability of each satellite design, a financial pro forma was developed from project initiation through the 10-year proposed lifecycle of the satellite constellation. The operating cost of the satellite constellation was assumed to be 12% of the total development cost across the lifetime of the constellation, based on operations of other satellites[22]. The assumed salary and benefit package of \$200,000 per year per employee continued through the lifecycle of the constellation. The revenue model is based off \$50 per month per subscriber. Due to the presumed vertical integration of the design and manufacturing, initial launches are assumed to begin within two years in 2020. Subscribers will begin to use the satellite connectivity service once the constellation has been fully deployed. Initially, it is assumed that the subscriber base will be at 500,000 users (13% market share of the 2021 satellite internet users). The subscribers are assumed to grow at a 50% compound annual growth rate (CAGR) through 2029. However, this growth is limited. The user base is not allowed to grow past the point where the constellation could support half of the users at 10Mbps, to ensure the system can still cope with peak demand. The weighted average cost of capital for the pro forma is calculated at 10%, which is in line with current technology and space industry estimates. The resultant cumulative net present value (NPV) of each downselected design is shown in Fig. 6.

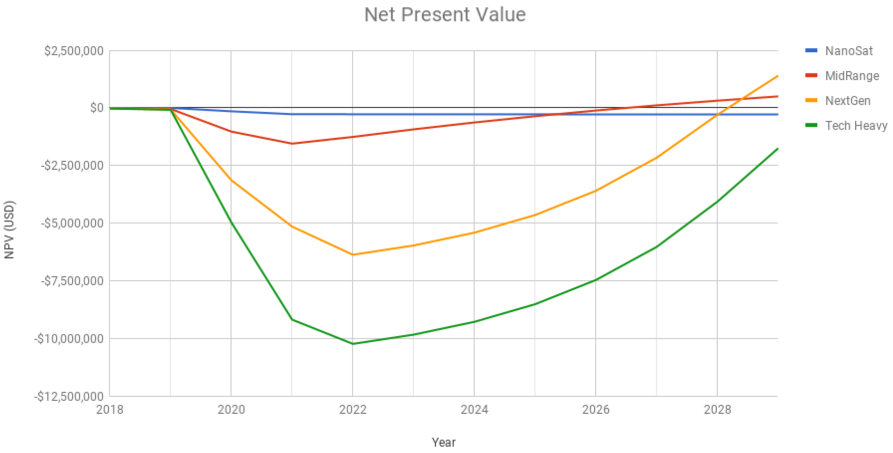


Fig. 6 NPV of Downselected Designs

B. Regulatory

For any of the designs, the implementation necessary to meet regulatory standards should not differ greatly from past constellations and telecommunications platforms.

To comply with regulations, broadcast licenses will need to be obtained, orbit debris analysis will need to be performed, and appropriate documents (such as end-of-life orbit plans) must be filed with the FCC (and equivalent organizations around the world), ITU, FAA/AST, State Department, and so on. These will need to be completed, like any other constellation.

The design should not have any additional regulatory hurdles. The only technologies that could be considered new or different on these satellites are electronically steered antennas, the use of AI (onboard or ground-based), and optical links. For electronically steered antennas, the regulations are likely identical to more traditional antennas. Any organization utilizing it will need to verify the regulations are equivalent. Like any other system, they will also need to verify that these regulations are met through analysis and testing. For AI-based systems on board, there will need to be software/hardware limits in case the algorithm acts unexpectedly. For example, if the AI attempts to allocate too much power to a downlink, a hardware or software limit should prevent this. Such an approach should satisfy any regulatory questions regarding AI, and is probably a smart move even if not demanded by regulations. Optical links are the one possible option that require additional regulatory actions. For optical crosslinks, the system will need to be cleared with the Joint Space Operations Center Laser Clearinghouse, in addition to the FCC and ITU.

C. Marketing

As a new player in the satellite internet market, any company will need a marketing strategy to recruit customers and build a reputation in this field. Of course, the ability to building a marketing strategy on the aspects being promoted are highly dependent on the design selected.

Emphasizing the ubiquity of coverage, low-latency connection, and high-throughput connectivity are all possible factors to use to attract individual clients. These could also be used to attract businesses, along with the emphasis on the security provided.

Some other key potential markets for the system are mobility (maritime and aviation, particularly), trucking, oil rigs, and network backhauling. These systems would not be marketed directly to consumers, but would require deals and agreements with airlines, shipping companies, trucking companies, and network providers. The best approach for this is having a system that is competitive in performance, reliability and price.

There is also the potential to use the network to enter other markets, besides satellite internet. One option would be partnering with cell phone companies to improve coverage and reliability in countries without developed fiber networks. Partnerships in this market could help gain access to new markets, particularly if we partner with data-intensive industries that typically rely on terrestrial networks. Using the system, they could expand into regions that were previously unavailable, due to lack of infrastructure, safety issues, or other problems.

Finally, rural areas are another key potential market for the system. This is a user base where large sections of the population either use satellite communications or could be well-served by satellite communications, given the lack of reliable alternatives. A network such as ours, that is high-throughput with extensive coverage, could appeal to these customers. In particular, it could compete with low-reliability or low-throughput broadband or cellular options. It is true the idea of satellite internet and cutting edge technology may pique some people's interests, but recruiting and retaining users will be most heavily dependent on customer experience. Therefore, any implementation will need a strategic focus on the customer experience. The customer cares mostly for the ways in which they interact with the system, including user terminals. In the internet service market, we can also aim to provide the service end-to-end. This would allow us full control over the network and the customer experience. Using this to focus on customer service and provide a top-notch delivery, we could reduce the frustration of the customers, provide a great experience when using our product, and command the highest possible margins.

D. Risks

Any enterprise carries risks, and this is especially true in the space industry, with its high upfront costs and complex technologies. A cutting-edge system and aggressive business case, as described here, carries an added share of risks as well.

The first group of risks are technological. This project would be at the forefront of satellite telecommunications and, therefore, relies on technologies that have not been used on this scale before. One key risk is the integration of these technologies. AI, electronically steered antennas, satellite crosslinks, and X-band satellite links have all been separately demonstrated, however they have not previously been combined in a consumer telecommunications network located in the harsh environment of space. There could also be unforeseen issues with integrating these technologies, causing cost and budget overruns, or requiring design alterations.

Though it is not a specifically new technology, there are a similar potential issues regarding a constellation of this scale. Without any previous systems of this size, it is difficult to predict the problems that will be encountered. Issues that do not occur in a system of 20 satellites might appear in a system of 200. Similarly, electronically steered antennas have been demonstrated, but not used as user terminal antennas on a large scale. These antennas may also experience new problems when in the field and subjected to the environmental and wear conditions of a user station. Finally, there may be an adoption hurdle for the users, as an electronically steered terminal could be quite different from those with which they are more familiar.

A second group of risks are more operational. Any satellite telecommunications network is complex to operate and requires many levels of bureaucracy and regulatory approval. As this project might be applied to new markets and use cases, there could be struggles in adapting the existing frameworks, on top of the issues inherent in all satellite communications projects. Establishing ground stations in multiple countries will require meeting their national regulations, which vary. This is not a huge risk, but should be taken into consideration, particularly given the new technologies and ideas that may be utilized. The regulations in many countries may not have caught up with new technologies, or may be punitively conservative regarding new concepts. General regulatory approval will also be needed from the FCC, ITU, and other organizations. This is a known process, but there may be new hurdles for new technologies (see Section V.B). Some of the markets and use cases under consideration may be more difficult. Using satellites to compete with 5G or as part of the 5G structure is different than previous cases. It is possible that this system, in the juncture of two previously separate domains, could face added restrictions, regulations, and requirements.

Finally, as with any business endeavor, this project carries market risks. We are making predictions of the market based on current trends and expert opinions. If the market grows less than predicted, or changes in a way that makes the system ill-suited, then the system may have fewer paying customers and generate less revenue, until an alternate market and use case can be found. On the other hand, if the market grows faster than predicted, there is the possibility of opportunity cost for having a system that is too limited or small-scale. One specific risk is, with the expanding satellite internet market, the price of satellite internet capacity decreases significantly. In that case, our revenue estimates, based on expected prices, would be invalid, and lower prices might be necessary to remain competitive. Similarly, growth in terrestrial networks could make the system less able to compete in certain markets. High-speed fiber networks, networks run by the community (rather than ISPs), and networks in areas that are currently underserved (such as rural areas) are particular examples which could cut into the predicted market. As mentioned previously, another risk is that the product (the user terminals or another aspect) is not well-received by consumers, reducing market penetration. If the cost of user terminals is prohibitively high, then consumers cannot afford to start services. The price of user terminals must be driven down to gain traction with a wider customer base.

Political and regulatory changes could also introduce market risk. One key example is net neutrality. With the overturn of net neutrality, many consumers could see their ISP increase their prices based on the content they access. In locations where there are few ISPs to choose from, a satellite internet product has the potential to benefit by offering a neutral product. If net neutrality is reinstated (or companies act neutrally on their own), then this market opportunity will not be present. On the opposite side of this, without net neutrality, there is the opportunity to partner with companies to distribute their content for free or reduced prices in markets that would otherwise be difficult to profit in (similar to Facebook's internet.org and Free Basics program). The reinstatement of Net Neutrality would remove this business case.

Many changes to the market could reduce the possibility for market share and thus revenue, but the changes could also offer opportunity. The risks and possibilities are hard to determine ahead of time, and could be caused by unpredictable circumstance.

VI. Conclusion

A. Summary Selection

Based on the detailed analysis comparing performance vs. cost and NPV of each system, the final recommendation is the "NextGen" design. The key characteristics of this selected design can be found in Table 4.

Table 4 Design Choice Characteristics

Designation	Mass [kg]	Frequency Band	Antenna Type	Crosslink Type	Relay Type	Architecture
NextGen	125	Ka/Ku	Electronically Steered	RF	Bent Pipe	Ring

Coverage	Altitude [km]	Estimated Constellation Size	System Capacity [Gbps]	Cost	2029 Subscribers	NPV
Global	444	312	1832.5	$8.9B	8M	$1.4B

The system's high NPV is the primary reason for our recommendation. Satellite communication companies have historically struggled with generating revenue; by optimizing over NPV, potential cash flow is the driving metric in determining next generation satellite communication systems. The constellation is able to provide nearly 2 Tbps across the system, which competes with Viasat-3. Furthermore, the high system capacity places this design as the ideal system to provide mobile broadband datarate (10 Mbps) at peak demand [4]. NextGen can service over 4 million users with 10 Mbps during peak demand.

NextGen provides high performance at an acceptable price. The low price per megabyte is an advantage, but it is also worth noting that it does not have excessive development costs. The NPV for NextGen is at $1.4B with the project's nominal market analysis. Compare this with the "Tech Heavy" design where its very high development cost results in a negative NPV of -$1.75B.

NextGen is a truly global constellation; global coverage is desirable because it offers customers internet anytime, anywhere; for comparison, the MidRange design technically provides global coverage, but the satellite system does not have crosslinks, which greatly limits connectivity. This causes issues over oceans (where there is a high mobility market demand) since it is difficult to install ground stations. Having a constellation with crosslinks, like NextGen, also reduces the total number of ground stations required, reducing the cost of the whole project. Furthermore, crosslinks allow for live health monitoring of the system and make the system more robust by enabling alternative routing in the case of system degradation. Finally, the crosslinks allow the system to tap the potentially lucrative maritime and aviation markets, meaning that the system could bring in more revenue than simply by providing satellite internet, meaning the revenue, value, and NPV may be even higher than we have predicted.

B. Comparison to Reference Cases

The selected design, NextGen, outperforms some of the reference cases. ViaSat-3 has already been deployed and both NextGen and Starlink are under development, making it difficult to perform more than a high-level analysis. A more thorough analysis on announced specifications and market estimations is likely to be inaccurate. This is especially true in the satellite industry, as many projects take much longer and cost much more than advertised. More specific design and performance comparisons are show in Table 5. It should also be noted that the reported cost of ViaSat is low, as it only includes manufacturing costs, and does not include launch or development costs.

Table 5 Design and Performance Comparisons

Feature	NextGen	ViaSat-3	Starlink
Orbit	LEO	GEO	LEO
Coverage	Global	Regional	Global
Constellation Size	312	3	4,425+
Mass [kg]	125	6,400	400
Latency [ms]	25	638	25
System Capacity [Gbps]	1833	3,000	88,500
Cost [$B]	$8.9	$1.9	$10

Compared to ViaSat-3, “NextGen” is superior in latency and disaggregated risks. As ViaSat-3 is in GEO, the round-trip time for a signal is, at best (with the satellite directly overhead) nearly half of a second. This is too long for voice communication or video conferencing, and is even long enough to make webpages load more slowly. Any sort of interactive information, or communication that requires a back-and-forth, is going to be dramatically slower and feel very “laggy” to users. NextGen, which is only at 1/70th of the altitude, will have much less of an issue. NextGen has a capacity of nearly 2 Tbps, putting it in the same class as ViaSat-3. In addition, with dynamic resources allocation, the system should be able to better utilize this capacity. The final advantage to “NextGen” over ViaSat-3 is the number of satellites. By deploying 312 satellites instead of 3, the impact of a single failure is greatly reduced. Satellites can be replaced, if needed, for significantly less cost, and each satellite handles a smaller fraction of the data, making any problems less catastrophic. This ties in with the use of crosslinks, as well. Data can be routed around problem satellites, and nearby satellites can help transmit to various locations. Data can be routed a multitude of different ways, through the crosslinks or on the ground, which can allow for more efficient usage of the network and better throughput overall. tNextGen has a number of advantages over ViaSat-3 including lower latency, higher system capacity, and disaggregated risks. For more in-depth information on ViaSat-3, see Appendix D.

For Starlink, we found it impossible to outperform the current cost, schedule, performance, and technology claims made by SpaceX. Since it was not possible to beat this system, a feasibility study was conducted to see if the system will be a potentially outperforming competitor. Our analysis indicated that Starlink will not be a commercially successful venture due to cost sensitivities, lack of historical precedent for necessary funding, and competing internal R&D funding priorities within SpaceX. For more in-depth analysis, see Appendix F.

Furthermore, the “Tech Heavy” solution shares many similar attributes to the Starlink, with optical crosslinks, a regenerative payload, slightly heavier mass (480 vs. 400 kg), and LEO altitude. Though “Tech Heavy” has significantly fewer satellites (203 vs. 4,425) and less technology on board, NPV analysis indicates that it will lose nearly $2 billion (though this may be connected to it not being a global system). It is worth noting that SpaceX has made grandiose claims (such as the Falcon Heavy) in the past, and eventually delivered, so it is possible that some form of Starlink may eventually succeed. However, though it was eventually successful, the Falcon Heavy was delivered years later than originally anticipated. The most likely case for Starlink to succeed is with a modified schedule, costs, and performance estimates. Without changes to current claims, it is unlikely to have a positive NPV or make enough money from the incurred costs. For more information on current Starlink plans, see Appendix E.

C. Sample Strategic Plan

Demand for data and connectivity is forecasted to grow exponentially in the foreseeable future. Terrestrial networks will attempt to expand with the growing demand, but could struggle to meet all needs [23]. Satellite internet capacity needs to to be expanded in order to meet this demand, and there is a clear market opportunity in this fast-growing market. Satellite internet could also play a key role in the 5G rollout. Hybrid networks will prove to be essential in providing internet connectivity to everyone in the world. An additional strong component in the favor of satellite internet is that current Net Neutrality rules may make satellite internet more appealing for customers [24].

The goal for implementing this technology going forward should be to compete on performance and cost, with a customer-oriented solution. To achieve this, a new satellite internet provider should partner with consumer-facing companies to find user-friendly solutions that easily interface with people's lives. In order for this satellite constellation to be effective, investments must be made in consumer-based hardware, such as affordable user terminals and cell phone plug-ins for satellite connectivity. There is also the opportunity to expand the role of satellite internet through operating services, such as WiFi cafés for rural villages.

With this consumer-oriented focus, a satellite internet provider would be able to develop a strong retail presence. Emphasis needs to be placed on sales channels, industry partnerships, and product architecture. By creating a vertically integrated system from design to manufacturing and through to service-based operations, the company will have greater control over the entire ecosystem. This will allow the provider to capture the larger margins that are available closer to the end-users.

Appendices

A. Specification of Metrics

Table 6 Summary of Cost and Performance Estimates

Decision	Option	Cost	Performance Inputs
Crosslink Type	None	0	$clf = 1$
	RF	3	$clf = 3$
	Optical	9	$clf = 6$
Antenna Type	Parabolic/Horn	8	see Appendix C
	Electronically Steered	10	see Appendix C
	Laser	9	see Appendix C
Coverage	Global (pole-to-pole)	10	$n_{\text{sats}} = 213$ $gf = 12$
	Effective Global (±60°)	7	$n_{\text{sats}} = 183$ $gf = 6$
	Equatorial (±45°)	6	$n_{\text{sats}} = 160$ $gf = 1$
Relay Type	Bent Pipe	2	$L_{\text{relay}} \propto n_{\text{sats}}$
	Regenerative	10	$L_{\text{relay}} \propto n_{\text{sats}}$
Constellation Architecture	None	0	$arch = 1$
	Ring	3	$arch = 3$
	Mesh	10	$arch = 7$
Dynamic Resource Allocation	Yes	2	$\eta_{ra} = 1$
	No	3	$\eta_{ra} = \frac{1}{6}$
User Terminal Type	Parabolic	1	$g_{rt} = 0.3$ dB
	Optical	10	$g_{rt} = 5.24$ dB
	Electronically Steered	10	$g_{rt} = 10.8$ dB
Mass	<10	1	$m = 10$
	10-100	2	$m = 45$
	100-500	5	$m = 200$
	>500	10	$m = 500$
Frequency Band	X-band	4	$f = 7.8$ GHz $L_{\text{atm}} = 0.61$ dB reuse = 4
	Ku/Ka-band	5	$f = 12$ GHz $L_{\text{atm}} = 0.97$ dB reuse = 4
	V-band	8	$f = 40$ GHz $L_{\text{atm}} = 7.42$ dB reuse = 7
	Optical	2	$\lambda = 1550$ nm $L_{\text{atm}} = 10$ dB reuse = 1

B. Cost Metrics

A. Antenna Type

Options: Parabolic, Phased Array, or Laser. See Table 7

Table 7 Summary of Cost Estimates for Antenna Type

Antenna Type	Parabolic	8
	Phased Array	10
	Laser	9

The costs for parabolic and phased arrays are based off satellite communication systems for yachts. The cost of a laser system is based of MIT STARlab's internally developed system. Intellian's 65cm Ku-band gimballed parabolic dish can be acquired for approximately \$20,000. STARlab estimates the raw material cost of their laser system to be approximately \$20,000. Commercially, phased arrays for satellite ground stations can be acquired for as low as \$1,000 each from ThinKom Solutions for example. However these arrays include only single transmitter and receiver. Experts estimate the cost of multi-transmitter and multi-receiver phased arrays being substantially higher than of their single channel counterparts. There have been no commercial satellites deployed with laser based system for ground communication. Comparably there is limited heritage of phased arrays on commercial satellites.

We took a conservative approach towards placing cost estimates on the antenna types since it is the main payload. Because we do not have a price point for a multichannel phased array antenna it gets a maximum cost rating of 10. Due the low heritage of lasers and their beamforming limitation they receive a cost estimate of 9. The parabolic dishes have extensive heritage, known design cycles but their limitation and high cost stems from required gimbal system, high mass and volume. Parabolic antennas receive a cost estimate of 8.

B. Crosslink Type

Options: Radio Frequency, Optical, or None. See Table 8

Table 8 Summary of Cost Estimates for Crosslink Type

Crosslink Type	RF	3
	Optical	9
	None	0

The cost estimate for crosslink type is based of the Antenna type discussion. However the cost of the RF system is assumed to be much lower than for the optical system because of lower pointing requirements and allows for multiple satellite communication in parallel. The optical system will require an individual laser for each link. Furthermore, optical crosslinks do not have extensive heritage, which poses additional development cost and program risk. Therefore the optical system is given the same rating as of laser antenna type. Meanwhile due to lower risk, more heritage and more lenient pointing requirements RF gets the cost rating of 3 compared with optical's 9. The None crosslink type has been given a cost score of zero.

C. Coverage

Options: Global, Effective Global, or Equatorial. See Table 9

Table 9 Summary of Cost Estimates for Coverage

Coverage	Global	10
	Effective Global	7
	Equatorial	6

The cost metric of coverage is based of the estimated number of satellites, number of orbital planes and relative inclination to the launch latitude. For a simple communications payload (field of view 60°, 3° overlap between satellites at 400 km altitude) then global coverage requires 4140 satellites, effective global (±65°) requires 2944, while equatorial requires 2024. Considering only the number of required satellites, Global gets a cost rating of 10, Effective global 8 and Equatorial 5. Due to the size of Global constellation we can assume we will get lower launch cost per satellite, hence we increase the cost of Equatorial to 6. However we reduce the cost of Effective Global by one point as the launch maneuver to deliver a satellite to polar orbit is higher than for regular inclined orbits, hence Effective Global has a rating of 7.

D. Relay Type

Options: Bent Pipe or Regenerative. See Table 10

Table 10 Summary of Cost Estimates for Relay Type

Relay Type	Bent Pipe	2
	Regenerative	10

Regenerative relays have not been commercially flown, therefore it is assumed they have limited heritage and have a steep price point. Meanwhile bent pipe relays have been flown for decades, as a result bent pipe gets a cost score of 2 and regenerative receives maximum score of 10.

E. Architecture

Options: None, Ring, or Mesh. See Table 11

Table 11 Summary of Cost Estimates for Architecture

Architecture	None	0
	Ring	3
	Mesh	10

Mesh architecture has been defined as the capability to form a crosslink with any of its neighboring satellites. This will materialize as requiring communications capabilities on four additional faces of the satellite, increasing costs, pointing, data handling, and weight. Therefore Mesh gets a cost rating of 10. Ring architecture is defined as the capability to communicate to the satellite in your orbital plane, resulting in crosslinks located on two additional faces of the satellite. Ring was given a cost estimate of 3 based on it is substantially simpler crosslink interface and less surface area constraint. Having no architecture does not incur any costs.

F. Dynamic Resource Allocation

Options:Yes or No. See Table 12

Table 12 Summary of Cost Estimates for Dynamic Resource Allocation

Dynamic Resource Allocation	Yes	2
	No	3

It was assumed that the developmental cost of making a dynamic resource allocation software would lower the lifetime cost of the constellation, by lowering operator costs relative to development cost. Therefore having dynamic resource allocation gets a cost rating of 2 while not having one receives a score of 3.

G. User Terminal Type

Options: Parabolic, Electronically Steered, or Optical. See Table 13

Table 13 Summary of Cost Estimates for User Terminal Type

User Terminal Type	Parabolic	10
	Electronically Steered	1
	Optical	10

Given that we are a LEO constellation, the user terminals need to be able to track the satellite as it traces over the sky. Therefore the common parabolic VSAT terminal pointing towards a GEO satellite will not suffice. This brings us back to the $\approx$ \$20,000 yacht gimballed parabolic antenna. On MIT campus there is ongoing research into making an optical ground station, with an estimated cost of the custom system in the tens of thousands of dollars. Meanwhile, electronically steered user terminals can passively track the satellites and we have already mentioned single transmitter/receiver phased array which is priced at $\approx$ \$1,000. Other options for electronically steered or flat panel antennas are Isotropic Solutions Limited (ISL) and Kymeta Corp.'s antennas which are projected to radically lower component costs. As a result electronically steered antennas get a cost estimate of 1, meanwhile parabolic and optical receive a cost score of 10.

H. Frequency Band

Options: X-Band, Ku/Ka-band, V-band, or Optical. See Table 14

Table 14 Summary of Cost Estimates for Frequency Band

Frequency Band	X-band	8
	Ku/Ka-band	5
	V-band	4
	Optical	2

There are several factors that went into the frequency band cost estimate, most notably the available frequency from FCC and ITU to get spectrum allocated and the estimated cost, risk and heritage of pre-antenna electronics. As a result of the congested spectrum of X-band receives a cost score of 8, the Ku/Ka-bands are not yet congested but is rumored to be allocated to terrestrial 5G receives a cost score of 5. However V-band has neither of the previously mentioned problems, but it is limiting by its physical frequency and sophisticated electronics to operate with the spectrum, therefore a score of 4 has been assigned. The optical spectrum is not regulated by the FCC but by FDA, technically it is not regulated of specific frequency bands but rather by maximum power flux hence optical receives a cost of 2.

C. Performance Algorithm

Our performance algorithm is defined by Eq. (17). The purpose of the performance algorithm was to creating a ranking systems for system down-selection.

$$P_{\text{sys}} = P_{Tx} + G_{Tx} + G_{RT} - L_P + 10\log_{10}(c_{PS}) + 10\log_{10}(\text{lat}) - k - L_{\text{relay}} + gf - L_{\text{atm}} + R_{cl} \tag{17}$$

These variables are broken down and explained below.

- Transmit power (P_{TX})
  - The power generated on the satellite is proportional to the available transmit power
  - $P_{TX} = 10\log_{10}(1360 * 0.3 * \eta_{RA} * SA)$
  - 30% is the solar array efficiency
  - $SA = m^{\frac{2}{3}}$
  - η_{RA} varies with dynamic resource allocation and SA varies with satellite mass
- Transmitter gain (G_{TX})
  - Equation being employed is dependent on the antenna technology.
    - Parabolic: $G_{TX} = 20\log_{10}\left(\frac{\eta_a \pi d}{\lambda}\right)$
    - Phased Array: $G_{TX} = 20\log_{10}\left(\frac{4\pi SA\eta_a}{\lambda}\right)$
    - Laser: $G_{TX} = 10\log_{10}\left(\frac{4\pi}{\Omega}\right)$ where Ω is the solid angle of the HPBW
  - Assumed constant orbital altitude of 400 km throughout
  - Varies with frequency and mass (SA)
- Receiver Gain on Noise (G_{RT})
  - Based off O3b, Starlink, and PorTel ground systems
    - Parabolic, O3b: $G_{RT} = 5.24$
    - Phased Array, Starlink: $G_{RT} = 10.8$
    - Optical, PorTel from MIT STAR Lab: $G_{RT} = 20\log_{10}\left(\frac{\pi D_{rx}}{\lambda}\right)$
- Path Loss (L_P)
  - Assumed constant orbital altitude of 400 km
  - $L_p = 10\log_{10}\left(\left(\frac{\lambda}{4\pi d}\right)^2\right)$
- Capacity Per Satellite (c_{PS})
  - Function of architecture, bandwidth, reuse factor, and crosslink factor
  - The variable cl is an integer that scales with architecture decision and crosslink factor
    - The architecture choice is a vector of 1, 3, and 7, where each number represents the theoretical number of connections a satellite in each architecture may have. One indicates no architecture, where only downlink and uplink with the ground are an option. Three indicates a ring architecture where a satellite in an orbital plane can transmit and receive from the ground, the lagging satellite, and the leading satellite. Seven indicates a mesh architecture that can transmit and receive from the same satellites as the ring, but also satellites in neighboring orbital planes.
  - The crosslink factor, clf acts as a performance multiplier vector with values 1, 3, and 6 corresponding to decisions: no crosslink, RF crosslink, and optical, respectively.
  - $cl = clf * arch$
  - Crosslinks add to the capacity of the system. It's assumed at any given time, the satellite is free to use its allocated bandwidth to perform crosslinks. The reuse factor further increases the usable bandwidth of the satellite.
  - $c_{ps} = reuse * BW + cl * BW_{CL}$.
- Latency ("lat")
  - Varies by constellation architecture and crosslinks
  - Latency, a metric with units of time, was based on the system's ability to get the information to ground once it was received.
  - Assuming no supporting ground infrastructure to help route data to users, systems without crosslinks would take an orbital period to deliver data to users.
  - With crosslinks, this latency was reduced by sending data to neighbors; within the crosslink design decision are two architectures: ring and mesh. Ring architectures were limited to sending data to spacecraft directly in front of or behind itself in the same orbital plane, making the latency factor smaller, but not as fast as it

could be. Mesh architecture allows for systems to communicate cross-plane and with no regard to where the target spacecraft lies in formation as long as it's in line-of-sight. This allows for the least amount of system latency.

- Relay Loss (L_{Relay}) (adapted from [10])
  - Bent Pipe: $10\log_{10}(n_{\text{sats}})$
  - Bent pipe systems are subject to noise and have no on-board processing to help preserve the received data. Received signals are filtered and amplified, but this leaves room for amplifying erroneous signals. This implies each time a signal is passed through a bent-pipe satellite, the noise power increases. To account for the worst-case of signal to noise ratio, it is assumed the signal will need to travel through every satellite in the constellation.
  - Regenerative: $10\log_{10}\left(\sqrt{n_{\text{sats}}}\right)$
  - Regenerative systems have the ability to demodulate and decode the received signal to better preserve the data and mitigate the effects of noise. This process greatly reduces the probability of making an error, however it is not a perfect process and the SNR is degraded by a square-root factor of the worst-case (traveling through all satellites).
- Global Factor (gf)
  - Assumes at any given time at any given location there are a number of satellites with 3dB extra power beam down to user. Varies by coverage. The less coverage, the less assistance a satellite gets from a neighbor
- Atmospheric Losses (L_{atm})
  - Determined for each frequency band Assuming 50 km travelled in sea level atmospheric conditions, MATLAB's internal `gaspl` function was used.
- Crosslink Rate (R_{cl})
  - The rate at which satellites can transmit and receive to one another in space, directly related to the satellite mass decision.

D. Reference Case: ViaSat-3

The new ViaSat-3 systems consists of three geostationary satellites which service the Americas, EMEA, and Asia providing service by 2019, 2020, and 2021, respectively. The most recently published cost estimates have indicated a price of $625M per satellite, although news has hinted towards price increase. The system is being built by Boeing and is expected to have a lifespan of 15 years. The systems has circular polarization with a four frequency reuse pattern with operators able to adapt the system where demand is unexpectedly higher or lower. The capacity of each satellite is estimated to be >1 Tbps, with residential broadband expected to provide 100+ Mbps data rates. The system operates in the Ka-band. The beam and channel characteristics can be seen in Tables 15 and 16.

From a business perspective, there is a strong focus on changing current residential broadband business plan. ViaSat has removed hard cap Internet plans, where your service is restricted after a hard cap has been met and has replaced it with a "soft cap". In this system when the daily limit has been reached, the customer is able to use any available bandwidth on the network, with speeds likely slower. While the heaviest streamers and gamers are not a good fit for satellite internet, ViaSat is targeting markets where customers currently only able to get 10 Mbps. The US Market is relatively untapped with 10-15 million households being underserved or unserved by ISPs. Currently, ViaSat has 690,000 residential broadband subscribers in the United States. With ViaSat-1, the company is hoping to expand to international markets. The targeted markets can be seen in Table 17. Trials have started in Northern Mexico for this service. The the global demand for consumer broadband is viewed as "pent-up" and "just a question of bringing the capacity online" by recent ViaSat Statements. The ground system for ViaSat-3 is expected to have 250 gateways with <2 meter antennas costing around $1M each. This is a paradigm shift from ViaSat-1 and ViaSat-2, which had 20 and 25 gateways, respectively and cost millions of dollars each.

Table 15 ViaSat-3 beam formulation, G/T, and EIRP

Characteristic	**A-Type Beam** (Operation Functions)	**B-Type Beam** (Service to End Users)
Beams	20	72
G/T (dB/K)	17.1 - 21.9	18.2 - 22.7
Peak Downlink EIRP (dBW)	56.9 - 62.2	62.7 - 67.0

Table 16 ViaSat-3 frequency, modulation type, and channel access method for forward and return links

Characteristic	**Forward**	**Return**
Frequency	28.1-29.1 GHz and 29.5-30.0 GHz	18.3-19.3 GHz and 19.7-20.2 GHz
Modulation Type	16-APSK, 8PSK, and QPSK	8PSK,QPSK,and BPSK
Channel Access Method	TDM 500 MHz wide carrier	MF-TDMA multiple bandwidths/data rates

Table 17 ViaSat-3 targeted markets by location

Americas	**EMEA**	**Asia***
Consumer Broadband	Residential Broadband	Commercial Aeronautics
Commercial Aeronautics	Commercial Aeronautics	Government (US)
Government	Government	
Enterprise Services		
Energy		

E. Reference Case: StarLink

In November 2016, SpaceX filed for a Ka/Ku Band frequency allocation with the FCC. In the application, SpaceX proposes using the spectrum to provide global broadband service via a Low-Earth Orbiting (LEO) satellite constellation known as "Starlink". In total, Starlink will be comprised of 4425 satellites in 5 altitudes using Ka/Ku band, with 1600 in 1 altitude, and 2825 in 4 different altitudes. It should be noted SpaceX also filed for a V Band frequency allocation for 7518 satellites in Very Low Earth Orbit (VLEO). Team Charlie did not consider the VLEO part of the system because of the role definition (i.e. designing a state-of-the-art communication system in LEO), and to simplify the Starlink case in the design space.

Each spacecraft has a projected average capacity of 20 Gbps, with an aggregate system capacity of 88.5 Tbps (full system deployment). SpaceX advertises Starlink can provide end-users with up to 1 Gbps using space terminal phased arrays, user terminal phased arrays, beamforming, optical crosslinks, and intelligent digital processing technology. Beam and channel characteristics can be found in Tables 18 and 19. The use of space terminal phased arrays enables electronically steered spot beams and the ability to employ beamforming. The use of user terminal phased arrays enables precision spacecraft tracking and relaxes the mechanical requirements needed to slew.

SpaceX plans to incrementally deploy LEO spacecraft for operations. The "beta" deployment consists of 800, single-altitude satellites that will provide service the US; the "initial" deployment will be the beta deployment and 800 more satellites (i.e. a 1600 total spacecraft) that provide global coverage to +/- 60° latitude; the "final" deployment consists of the remaining 2825 satellites that provide complete global coverage (pole-to-pole service).

Table 18 Starlink Beam Formation, G/T, and EIRP Schedule S Values

Characteristic	**Gateway Beam** (Operation Functions)	**User Beam** (Service to End Users)
Beams	4	16
G/T (dB/K)	13.7 - 8.7	9.8 - 8.7
Peak Downlink EIRP (dBW)	39.44 - 0	39.44 - 0

Table 19 StarLink Frequency Allocation and Modulation Type

Characteristic	**Uplink**	**Downlink**
Frequency (GHz)	14.0 -14.5 27.5 - 29.1 29.5 - 30.0 47.2 - 52.4	10.7 - 12.7 17.8 - 18.6 18.8 - 19.3 37.5 - 42.5
Modulation Type	BPSK, QAM	OQPSK, QAM

F. Starlink Feasibility Study

Since the systems being considered are all direct competitors to Starlink, a review of publicly available information was completed in order to determine the feasibility of Starlink from a business perspective. With the amount of technology Starlink has reported to include on their satellites, including optical crosslinks, regenerative payloads, V-band hardware, and electronically steered arrays, a separate study would need to be considered for the technical and programmatic risks. It is unclear how much of this technology was included on the recent test flights, where the satellites weighed 400 kg [8] . The most recently released information anticipates an operational constellation of 800 satellites by 2020 [8, 11]. There will be a total of 4,425 satellites by 2027, with a possible total of 7,725 satellites beyond 2027 [8, 11]. Estimates from industry sources indicate the cost of a Falcon 9 to be $37M [25]. The number of employees is estimated to be at least 60 considering the current number of open positions (there are 33 open positions [26]) and is expected to grow to 1,000 by 2020 [27]. While the current satellite cost remains unknown, the development, launch, and satellite constellation costs are estimated in Table 20.

Table 20 Cost build up of Starlink

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Employees	50	240	430	620	810	1000	1000	1000	1000	1000	1000	1000
Satellites deployed	0	0	0	100	450	800	1153	1506	1859	2213	2950	3688
Sats/Year	0	0	0	100	350	350	353	353	353	353	738	738
Launches/Year	0	0	0	3	9	9	9	9	9	9	17	17
Employee Cost ($M)	9	43	77	112	146	180	180	180	180	180	180	180
Launch Cost ($M)	0	0	0	111	333	333	333	333	333	333	629	629
Sat Cost (Low) ($M)	0	0	0	100	350	350	353	353	353	353	738	738
Sat Cost (Med) ($B)	0	0	0	0.5	1.75	1.75	1.8	1.8	1.8	1.8	3.7	3.7
Sat Cost (High) ($B)	0	0	0	1	3.5	3.5	3.5	3.5	3.5	3.5	7.4	7.4
Subscribers Needed (Low) (k)						681	683	683	683	683	1,220	1,220
Subscribers Needed (High) (M)						9.5	9.5	9.5	9,571	9.5	19.4	19.4

With the large number of satellites, the cost of the system is unsurprisingly very sensitive to the cost of the satellite. Three different satellite costs were estimated: $1M (low), $5M (med), and $10M (high), resulting in three different total constellation costs at $10B, $28, and $50B. SpaceX has publicly estimated the constellation cost to be $10B, as well, suggesting a satellite cost of $1M [28]. Considering the amount of unproven technology on the satellites, this number seems remarkably low. Likely, Starlink is relying significantly on savings due to mass production. However, if parallels may be made to Elon Musk's other company, Tesla, mass production efficiency takes years to achieve and can be elusive. From the NYTimes, the company aimed to produce "20,000 Model 3s a month by December. More recently, Tesla had aimed to produce at least 2,500 Model 3s per week by the end of the first quarter. But that is more than it managed in the entire fourth quarter, and it has produced fewer than 10,000 in the first quarter, the company said Tuesday," [29]. The likelihood of making a satellite for <$1M without production expertise is very unlikely.

As can be seen from the results of the cost build up, Starlink quickly moves from a "feasible" $10B cost to multiple tens of billions, still using satellite prices that are unheard of for the technologies involved, including optical crosslinks, regenerative payloads, electronically steered arrays, and untested V-band flight hardware. Historically, satellite endeavors have only raised single-digit billions of dollars considering Iridium NexGen ($2.9B), OneWeb ($1.7B), and O3B ($1.2B) [30–32]. Over 16 years, SpaceX itself has only raised $1.58B [33].

Considering the customer base that would generate revenue for this constellation, Starlink would require 1M subscribers in the low case and 20M in the high case. This assumes that subscribers cannot start to use the service until it is operational in 2020, and that the average price is $50 / subscriber (used in high case) or $150 / subscriber used in low case), It also assumes a 40% margin. These margins are likely necessary in order for Starlink to generate a return on investment and help fund BFR, which has been speculated. This margin was pulled from IntelSat's 2017 10k for reference. The current consumer broadband service market had 1.9 million subscribers in 2016, according to 2017: State of the Satellite Industry report. This means that Starlink will need to at least double the current market in order to make money in the best possible scenario report. In the worse case, Starlink would need to exponentially grow the consumer base. Without investing in affordable user terminals, which can cost up to $1,000, it will be difficult to grow the user base.

Additionally, Starlink appears to be a competing priority for BFR, which is consuming a large portion of SpaceX's R&D expenditure. It is unclear how SpaceX can focus on two capital-intensive long term investments at the same time. SpaceX has had a single priority in the past of building rockets and moving to multiple competing priorities may prove difficult.

Finally, due to the unfeasibly low satellite cost of $1M, relatively low fundraising for space ventures of $2B, large required number of subscribers, and SpaceX's internal competing priorities for R&D funding, Starlink should not been seen as a viable competitor with the currently stated constellation timelines, cost estimates, and configuration.

G. Constraints

Figure 7 shows the options from the morphological matrix decisions, limited by the constraints.

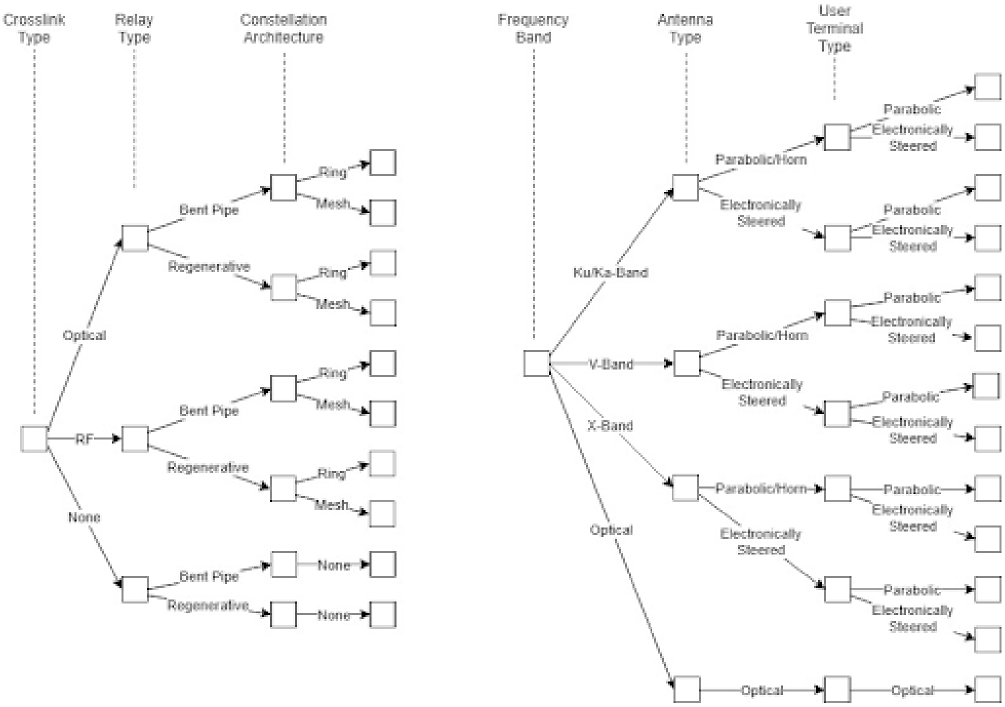


Fig. 7 Graphical Representation of Morphological Matrix Constraints

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